

## RHEOLOGICAL PROPERTIES OF ASPHALTS WITH PARTICULATE ADDITIVES

N. Shashidhar  
EBA Engineering  
5800 Metro Drive  
Baltimore MD 21215

Brian H. Chollar  
Federal Highway Administration, HNR-20  
6300 Georgetown Pike  
McLean VA 22101

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### INTRODUCTION

The Superpave asphalt binder specifications are performance-based specifications for purchasing asphalt binders for the construction of roads. This means that the asphalt is characterized by fundamental material (rheological) properties that relate to the distress modes of the pavements. The distress modes addressed are primarily rutting, fatigue cracking and low temperature cracking. For example,  $G^*/\sin(\delta)$  is designed to predict the rutting potential of pavements, where  $G^*$  is the magnitude of the complex shear modulus and  $\delta$  is the phase angle. The binder for a road that is situated in a certain climatic zone requires the binder to have a minimum  $G^*/\sin(\delta)$  of 2200 Pa at the highest consecutive 7-day average pavement temperature the road had experienced. Implicit in such a performance based specification is that the fundamental property,  $G^*/\sin(\delta)$ , of the binder correlates with rutting potential of the pavement regardless of the nature of the binder. In other words, the specification is transparent to the fact that the binder can simply be an asphalt, or an asphalt modified by polymers, particulates and other materials that can form a two-phase mixture.

There has been limited amount of research to validate the correlation of the Superpave binder parameters with laboratory mix tests and fewer still with pavement performance. The use of modified binders in such validation studies is further limited. Rarer still are studies that use particulate modifiers. Anderson and Kennedy<sup>1</sup> presented the basis for Superpave binder specification and validated these with mix tests. They did not specifically use modified systems, except when talking about low temperature cracking specifications. King et. al.<sup>2</sup> showed a good correlation between the low-temperature cracking predictors, namely, the temperature at which the failure strain is 1% and the temperature when creep stiffness is 200 MPa, to the thermal stress restrained specimen test (TSRST) for various asphalts and polymer modified binders. Hicks et. al.<sup>3</sup> validated the binder specifications with laboratory mixture testing using only unmodified binders. Bouldin et. al.<sup>4</sup> show excellent correlation between  $G^*/\sin(\delta)$  and wheel tracking tests, but limit the asphalts to unmodified and styrene butadiene-styrene (SBS) copolymer. In conclusion, the Superpave binder specifications were developed considering primarily unmodified asphalts. Though some validation studies (with laboratory mix tests) consider polymer modified asphalts, they are limited to binders containing modifiers that form a macroscopically homogenous system with the asphalt.

When the Intermodal Surface Transportation Efficiency Act of 1991 was passed, some testing of asphalt modified with ground tire rubber or crumb rubber modifiers (CRM) were reported<sup>5,6</sup>. In these papers the Superpave binder testing was simply applied to testing binder with fairly large (up to -10 mesh = 2 mm) particulates. It was not shown in these papers that the Superpave binder test methods can be used to predict the performance of such binders.

AASHTO provisional procedure PP5<sup>7</sup> deals with the separation of modifiers from asphalt on storing either by formation of the film on the surface or a sludge on the bottom. The practice further ensures that the base asphalt that is used to make modified binder is over 99% soluble. This implies that after passing this test any modifier (including a particulate modifier) can be used provided the modifier does not separate when left standing at 163°C for 48 hours. In a move to limit the kinds of modifiers that could be used, the FHWA Superpave Binder Expert Task Group (ETG)<sup>8</sup> decided "*that the material being evaluated using the Superpave binder specifications must be tested to satisfy the ASTM D5546 solubility criteria. If the material fails this test, it is up to the purchasing agency to accept or reject the material.*" Although such specifications on the use of particulates do impose some restrictions, they do not absolutely disallow the use of particulates. This perhaps should not be done since it will stifle any innovation. However, a basic understanding of the behavior of particulates in asphalt will allow for a more objective evaluation on the benefits (or lack thereof) of particulates in pavements.

Given that the development and validation of Superpave binder tests did not rigorously consider binders with particulate additives, several questions must be answered before the adoption of the Superpave binder specification nationally. These questions broadly fall into three categories:

- (1) When particulates are added to asphalt there are issues relating to segregation of the particulates due

to settling or other phenomena. There is the issue of maximum particle size below which the accuracy of measurements with the Superpave testing equipment will not be affected. There may also be other unknown issues that could affect the results. These issues can be summarized by the questions "Can the present Superpave testing procedures be used to test binders with particulate additives? Under what limitations can such modified binders be tested?"

- (2) How does modification of binders with particulate additives affect the Superpave grading of these binders? Can the changes in grading be predicted with the knowledge of parameters that completely characterize the rheology of particulate-binder system?
- (3) Will a binder whose PG (performance grade) grading is achieved by adding particulate modifiers perform the same as another binder of the same PG grade that is unmodified? In other words, will the changes in binder specification due to particulate modifiers truly reflect on the performance of mixes containing such modified binders in laboratory mixture tests and on the pavement performance?

Obviously, these are loaded questions and require extensive research. The third question above, is the most significant, for, if adding particulates to binders changes a property such as  $G^*/\sin(\delta)$  but does not really change the pavement performance, then the binder will have an inflated grade that will not be reflected in the performance. On the contrary, if the addition of certain particulates does enhance the performance of the roads, but this is not truly reflected in the current specifications, then methods must be developed to capture this enhanced performance.

An understanding of the asphalt-particulate system is fundamental to answering any of the above questions. This is the subject of this paper.

Evaluation of particulates in asphalt in the form of fines and mineral dust is not new, nor is the evaluation of particulate composites in polymers and other materials. There are hundreds of research papers that deal with this topic in the materials science literature. In asphalt literature, several investigators have tried to evaluate the effect of fines in asphalt concrete and have attempted ways to predict the stiffening power of fillers in asphalt. Tunnichliff<sup>9</sup> has reviewed the literature for mineral filler-asphalt systems prior to 1962. Another noteworthy paper is the report by Anderson<sup>10</sup> who gives insight into the role of mineral filler in asphalt. In the field of polymers, two recent reviews<sup>11,12</sup> and a book<sup>13</sup> summarize the developments in polymer-melt systems, highly filled systems and general treatment, respectively. The above is not meant to be a complete literature survey, but just a reference to key review papers.

### Description of asphalt with particulate additives

The description of the behavior of filled systems in polymer matrices has traditionally been approached from two directions—Einstein's equation<sup>14</sup> and its modifications for polymer liquid and melt systems, and the Kerner's equation<sup>15</sup> and Hashin and Shtrikman's equation<sup>16</sup> and their variations for polymer solid systems. These two approaches were brought together with the expression

$$\left( \frac{\eta}{\eta_1} - 1 \right) = \frac{2.50(8 - 10\nu_1)}{15(1 - \nu_1)} \left( \frac{G}{G_1} - 1 \right) \quad (1)$$

for the relation between viscosity and shear modulus<sup>17</sup>. Here,  $\eta$  is the viscosity,  $G$  the shear modulus,  $\nu$  is the Poisson's ratio. When the Poisson's ratio is 0.5, then

$$\frac{\eta}{\eta_1} = \frac{G}{G_1} \quad (2)$$

Thus, the equations developed for  $\eta/\eta_1$  should be applicable to  $G/G_1$ , and vice-versa. The convention used above will be that used in equations henceforth—subscript 1 denotes the matrix, 2 denotes the particulates, and the unsubscripted variables denote the binders with particulates (a composite property).

After an evaluation of many equations in the literature including the Einstein<sup>14</sup>, Mooney<sup>18</sup>, Roscoe<sup>19</sup>, Eilers-van Dijk<sup>20</sup> etc. (which will not be described in this paper) equations, the generalized Nielsen's equation<sup>13,21</sup> was selected for further analysis of asphalts. Nielsen's equation is a modification of Kerner's equation for elastic materials. However, this equation has been applied to many viscoelastic polymers successfully<sup>13</sup>. The Nielsen's equation describes the stiffness dependence on the volume fraction of particulates in terms to two fundamental properties of the system. It further provides a way to account for differences in the stiffness of fillers themselves, the particle-matrix interface energy, and other materials parameters. Such knowledge will help isolate the various causes for stiffening of binders when particulates are added.

Nielsen's equation describes the modulus ratio between the filled and unfilled system as follows:

$$\frac{M}{M_1} = \frac{1 + AB\phi_2}{1 - B\psi\phi_2} \quad (3)$$

where  $M$  is any modulus and  $\phi_2$  is the volume fraction of the filler. The constant  $A$  takes into account such factors as geometry of the filler phase and poisson's ratio of the matrix, the constant  $B$  takes into account the relative moduli of the matrix and filler phases; its value is 1.0 for very large  $M_2/M_1$  ratios.

$$B = \frac{M_2/M_1 - 1}{M_2/M_1 + A} \quad (4)$$

The factor  $\psi$  depends on the maximum packing fraction,  $\phi_m$ , of the filler. An empirical equation that satisfactorily describes the relation between  $\psi$  and  $\phi_m$  is

$$\psi = 1 + \frac{1 - \phi_m}{\phi_m^2} \phi_2 \quad (5)$$

The constant  $A$  is related to the generalized Einstein Coefficient  $K_E$  by

$$A = K_E - 1 \quad (6)$$

In the case of mineral fillers in asphalt, since the modulus of the filler is much higher than the asphalt, the value of  $B$  is unity. Substituting  $B=1$  and equation 5 in equation 3 will yield

$$\frac{M}{M_1} = \frac{1 + A\phi_2}{1 - (1 + C\phi_2)\phi_2} \quad (7)$$

where

$$C = \frac{1 - \phi_m}{\phi_m^2} \quad (8)$$

By curve-fitting equation 7 to the data, the constants  $A$  and  $C$  can be estimated. From these parameters, the generalized Einstein coefficient  $K_E$  and the maximum packing fraction,  $\phi_m$ , can be calculated.

Thus, if Nielsen's equation, obtained for filled polymer systems, can be used for asphalts, it is then possible to characterize an asphalt-particulate system using two fundamental properties,  $K_E$  and  $\phi_m$ . A knowledge of the variation of  $K_E$  and  $\phi_m$  for different asphalt-modifier systems as a function of properties of interest then lead to the selection of appropriate powders for better such properties. Although, this paper restricts the analysis to mineral fillers, this approach can be used for all modifiers used for asphalts as long as they do not completely dissolve in asphalt, but form a discrete, but dispersed phase.

## EXPERIMENTAL

Thirteen fillers that were used in a prior study<sup>22</sup> were used with an AC-20 from Venezuela's Lagoven base stock supplied by Koch Material's company, Pennsauken, NJ. Some of the properties of these fillers are listed in Table 1. The particle size distributions for all these fines are reported in a prior study<sup>23</sup>

The asphalt was used in its unaged state for all the experiments. Fines were added to asphalt to make 10 g batches of 4, 8, 12, 16, 20 and 24 volume percent particulates. Care was taken not to form agglomerates during the mixing process. The mastic was continuously stirred as it cooled down to prevent any settling. When the mastic thickened due to cooling, it was then transferred to silicone rubber molds to make pellets for testing with the dynamic shear rheometer (DSR).

Testing of the mastic was done with a Rheometrics RDA II dynamic shear rheometer (DSR) with a FTS torque transducer. The transducer was used in its most sensitive range (200 g-cm full scale). Strain

Table 1. Particulates used in this study<sup>†</sup>

Code	Sp. Gr.	Rigden Voids	Material
SWE2	2.84	36.5	Granite
SWE3	2.74	38.2	Granite
SWE5	2.91	37.3	Granite
SWE6	2.84	40.0	Granite
SWE7	2.74	33.1	Limestone
CHE1	2.76	38.5	Sandstone
CHE2	2.76	32.8	Limestone
GER1	2.74	35.2	Pure Limestone
GER2	2.87	34.8	Dolomitic Limestone
GER3	2.74	34.5	V. Pure Limestone
GER4	2.76	45.7	Granite
GER7	3.18	69.2	Fly Ash
GER9	2.74	38.2	Limestone

<sup>†</sup> Data from Reference 19

sweeps were measured at 25°C and 10 rad/s frequency with 8 mm parallel plate geometry and 2 mm gap and at 70°C with a 25 mm parallel plate and 1 mm gap. There has been discussion as to the maximum size particulates that can be used between parallel plates with 1mm gap. In these experiments we have avoided this issue by choosing fine particulates that have over 90 wt% below 75  $\mu$ m. The issue of maximum particle size will be addressed in later research.

## RESULTS

The strain sweeps obtained for asphalt with varying amount of fines are shown in Figures 1 (25°C) and 2 (70°C). This is a representative of data obtained for all the fines. The data was linear to over 1% strain at 25°C and to over 10% strain at 70°C. For further analysis, values at 0.1 % strain for 25°C and 1% strain at 70°C were considered.

When the ratio of  $G^*$  to  $G_1^*$  was plotted as a function of volume fraction of particulates ( $\phi_2$ ), behaviors such as illustrated in Figures 3 and 4 were observed. These figures also illustrate the curve-fit according to equation 7 And the 95% confidence limits for these curves. The curve-fit parameters are listed in Tables 2 and 3 for measured parameter  $G^*$  and  $G'$ , respectively. It must be noted that for the fines studied, the constant A varied from 1.2 to 6.6 with the exception of GER7 which had A values between 10.5 and 15.2. The constant C varied from 1.0 and 4.7 not including GER7.

The generalized Einstein coefficient  $K_E$  and the maximum packing fraction  $\phi_m$  calculated from the curve-fit parameters are listed in Table 2. The variation in constant A is reflected in variation of  $K_E$ . The  $\phi_m$  varied from 0.32 to 0.52 for all the powders. It is also interesting that  $\phi_m$  varied as little as 0.04 and as much as 0.12 between measurements at the two temperatures for a given particulate and asphalt. The key to using this approach is in the success in the interpretation of  $K_E$  and  $\phi_m$ .

Figure 5 shows the phase angle as a function of  $\phi_2$  at both 25°C and 70°C. This curve is typical of those of the thirteen mastic mixes in that there is no systematic variation in the phase angle with  $\phi_2$ . Also, the magnitude of variation is  $\pm 1^\circ$ . We can therefore conclude that the phase angle is not effected by the addition of mineral particulates up to 25 volume percent fines.

## DISCUSSION

When a powder fills a container, a fraction of the volume of the container is occupied by the powder particles while the rest are voids. The fraction of the volume of the container actually occupied by the powder is defined as the packing fraction,  $\phi_2$ . If the powder packs efficiently, then the volume fraction of

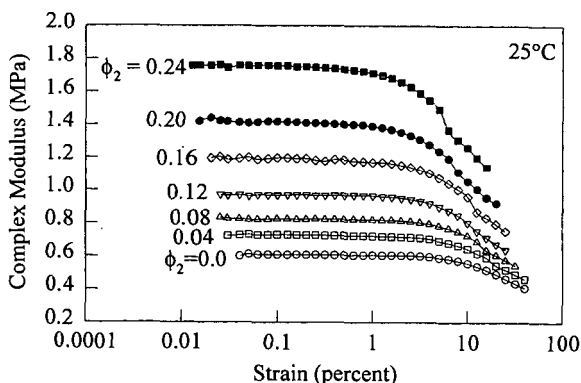


Figure 1. Strain Sweeps at 25°C for asphalt with different amounts of GER9. This is representative of all the powders.

powder in the container, and, hence, the packing fraction,  $\phi_m$  increases. The maximum packing fraction,  $\phi_m$ , is the highest value  $\phi_2$  can have, and is a function of the average particle size and particle size distribution. Anderson described two refined techniques for measuring  $\phi_m$ , namely, the dry compaction method and the kerosene method<sup>10</sup>. Since  $\phi_m$  is a fundamental property,  $\phi_m$  measured by an independent technique (such as Anderson's) should compare with the value from Nielsen's equation.

Figures 6 and 7 plots the correlation between the  $\phi_m$  from the dry compaction method of Anderson and the  $\phi_m$  obtained as described in this paper. This figure shows there is a poor correlation between the two techniques. The  $\phi_m$  from Equation 6 is consistently lower than the measured value.

In another example, we fit viscosity (25°C) measurements from Traxler<sup>24</sup> to Nielsen's equation and estimated the  $\phi_m$ . The correlation between the estimated  $\phi_m$  and the value measured experimentally<sup>24</sup> (by dry compaction in a glass graduate technique) is plotted in Figure 8. This, in contrast to the data in Figures 6 and 7, shows very good correlation.

Apparently, the success of Equation 7 in estimating  $\phi_m$  in Figure 8 indicates that the equation works in some situations. The problem is to identify when the equation works and how to best use it to gain an insight into the mastic.

A likely reason for disparity between the measured and calculated values of  $\phi_m$  is the fact that the  $\phi_m$  calculated from Nielsen's equation measures the true state of packing for particulates in asphalt, while the

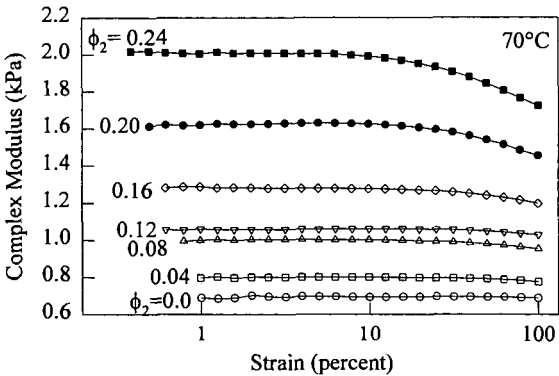


Figure 2. Strain sweeps at 70°C for asphalt with different amounts of GER9. This is representative of the behavior of all the particulates.

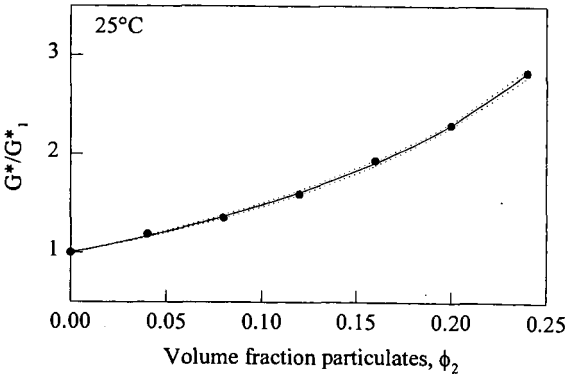


Figure 3. The change in  $G^*$  ratio as a function of  $\phi_2$  at 25°C. The solid line is a fit with the Nielsen's equation and the dotted lines are 95% confidence limits for the curve-fit.

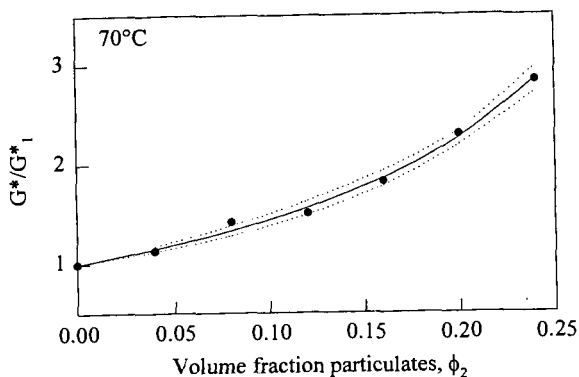


Figure 4. The change in  $G^*$  ratio as a function of  $\phi_2$  at 70°C. The solid line is a fit with the Nielsen's equation and the dotted lines are 95% confidence limits for the curve-fit.

dry compaction technique of Anderson measures an ideal case, a state that is unnatural for asphalt systems. The following factors would effect the packing of particulates in asphalt and, hence, the estimates of  $K_E$  and  $\phi_m$ <sup>13</sup>:

1. Any particle-particle interaction causing networks (structuring) among particles or formation of agglomerates would decrease the packing of particulates (decreasing  $\phi_m$ ). Such interactions will also reflect on higher estimates of  $K_E$ .
2. The aggregate shape and aspect will also effect the packing of powders. Higher aspect ratio of particles would increase the  $K_E$  and decrease the packing efficiency (decreasing  $\phi_m$ ).

On the other hand, the  $K_E$  measured for all the powders are close to the theoretical value of 2.5 derived for very dilute spheres<sup>14</sup>. This indicates that the approach is fairly successful in describing the mastic, and there are differences between the powders in terms of shape of particles, their interaction with the asphalt, etc.

Although there are several issues to be resolved, the use of Nielsen's equation allows for a fundamental approach to analyzing particulates and fillers in asphalts. In the asphalt literature, it has been reported that the Rigden voids (which is equivalent to  $1-\phi_m$ ) correlate most with the stiffening power of asphalts<sup>10,22</sup>. The approach presented in this paper indicate that a factor other than Rigden voids (and its equivalent  $\phi_m$ ), namely, the generalized Einstein coefficient  $K_E$ , also is an important property that predicts the stiffening power of the fines. In fact, both these parameters are equally important in predicting the stiffening power of particulates. These two parameters are a function of the asphalt-particulate system and characterize the system completely. The effect of both these parameters on the stiffening of asphalts will be discussed next in this paper.

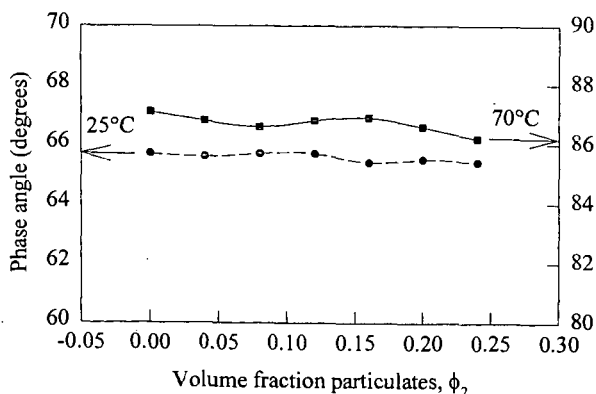


Figure 5. The change in phase angle as a function of  $\phi_2$  at 25°C and 70°C.

### Effect on PG grading

It has been shown that the increase in  $G^*$  with addition of particulates can be described if we know  $\phi_m$  and  $K_E$ . It was shown that for most of the mineral powders used in this study,  $\phi_m$  varied between 0.32 and 0.52 and  $K_E$  varied between 2 and 5. By analyzing how  $G^*$  varies for a range of  $\phi_m$  and  $K_E$ , one can predict to what extent the addition of mineral fillers are likely to effect the PG grading if the  $\phi_m$  and  $K_E$  are known.

In Figure 5, it was shown that the phase angle did not change with addition of particulates. This indicates that by the addition of particulates the master curve for the asphalt merely shifts towards higher  $G^*$  without undergoing any change in time dependence. Such a behavior is assumed for low temperature region as well. Since the  $m$ -value is equivalent to the phase angle, the independence of phase angle to the addition of particulates can be reasonably expected to reflect the independence of  $m$ -value also. This assumption has to be tested with actual experimental data. This is planned for future work.

The procedure described below was used to evaluate the effect of the addition of mineral fillers on the PG grade of asphalt:

1. The  $G^*/\sin(\delta)$  was plotted as a function of temperature and fit with a quadratic equation of the form  $\log(G^*/\sin(\delta)) = \alpha + \beta T + \chi T^2$ . From this equation the fractional grading (the temperature when  $G^*/\sin(\delta) = 2200$  Pa) for the binder was determined.
2. For  $G^*/\sin(\delta)$  at each temperature (52, 58, 64 and 70°C), the  $G^*/\sin(\delta)$  for binder with particulates were calculated for given values of  $\phi_m$  and  $K_E$  using Nielsen's equation.
3. We now have the estimated  $G^*/\sin(\delta)$  vs. temperature data for asphalt with different amount of particulates. For each  $\phi_m$ , a quadratic equation was fit as before to calculate the continuous grade of the mastic. It was found that only the constant  $\alpha$  varied with  $\phi_m$ , the constants  $\beta$  and  $\chi$  being invariant. The fraction grading thus estimated is plotted as a function of  $\phi_m$  and  $K_E$  in Figures 9 and 10, respectively.
4. A similar procedure was carried out for creep stiffness at 60 s. The change in fractional grade with the addition of particulates as a function of  $\phi_m$  and  $K_E$  are plotted in Figures 11 and 12, respectively.

The invariance of constants  $B$  and  $C$  with  $\phi_m$  is the result of assuming that  $\phi_m$  and  $K_E$  does not change with temperature. This assumption is consistent with our earlier reasoning that the addition of particulates merely shifts the master curve to higher stiffness. It can however be seen from Table 2 that  $\phi_m$  and  $K_E$  do not seem to be different at 70°C than it is at 25°C, which leads us to give credence to this assumption.

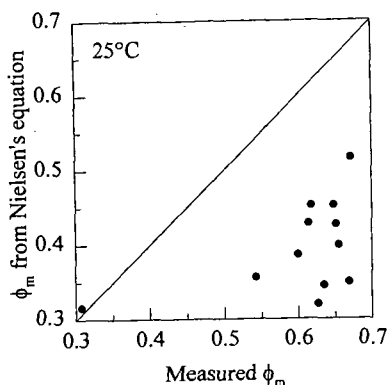


Figure 6. A comparison of  $\phi_m$  estimates from Nielsen's equation (25°C data) and measured by dry-compaction method.

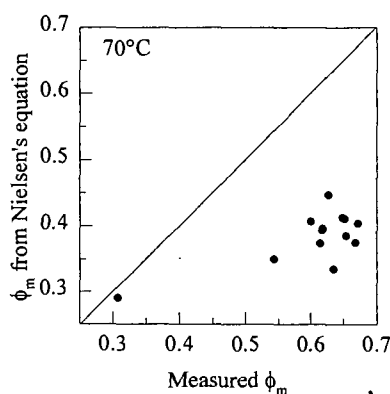


Figure 7. A comparison of  $\phi_m$  estimates from Nielsen's equation (70°C data) and measured by dry-compaction method.

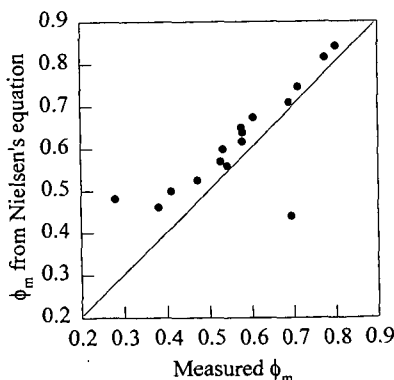


Figure 8. A comparison of  $\phi_m$  estimates from Nielsen's equation (25°C data) and measured by a different dry-compaction method. (Data from Ref. 22)

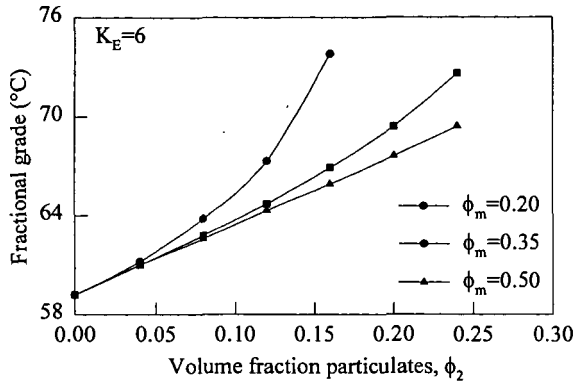


Figure 9. The effect of increasing  $\phi_m$  on the high temperature grade for RTFOT aged asphalts.

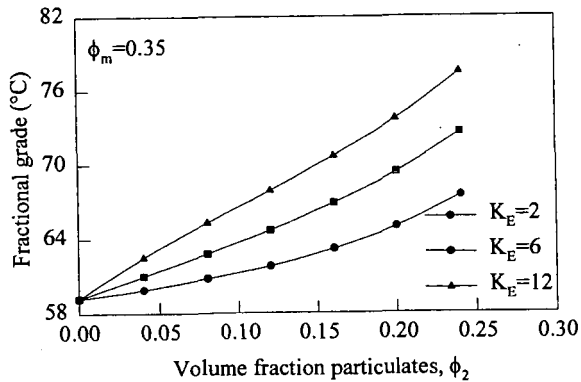


Figure 10. The effect of increasing  $K_E$  on the high temperature fractional grade on RTFOT aged asphalts.

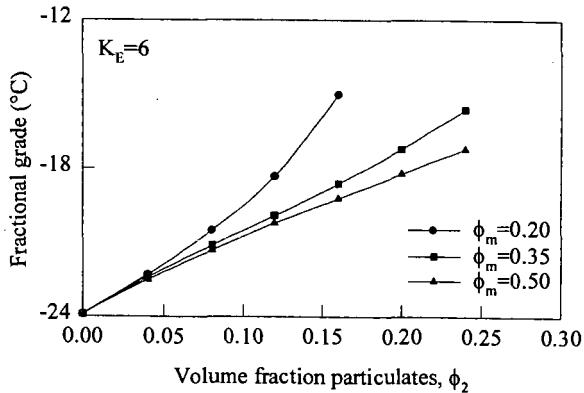


Figure 11. The effect of increasing  $\phi_m$  on the low-temperature fractional grading based on S.

The range of  $\phi_m$  and  $K_E$  selected for our study should represent many non-agglomerating mineral fillers. Close packing of particulates can yield a value of  $\phi_m$  higher than 0.5. Very poor packing caused by the hygroscopic nature of the particulates or existence of agglomerates can cause  $\phi_m$  to be less than 0.2. If the particulates are extremely fine, then the  $\phi_m$  and  $K_E$  can be very different.

From Figure 9 it can be seen that as fines are added to the asphalt, the high temperature grade increases



by six degrees (one grade) with the addition of 13% particulates when  $\phi_m$  is 0.35 and another grade with additional 10% fines. When the  $\phi_m$  is 0.5, it requires 16% for the first grade and additional 10% for the next grade. On the other hand, if  $\phi_m$  is closer to 0.2, it takes just 8% to increase  $G^*/\sin(\delta)$  by a grade and additional 5% for the next grade. Thus as  $\phi_m$  is reduced,  $G^*/\sin(\delta)$  becomes more sensitive to the addition of particulates.

Similarly, when  $K_E=2.0$  (Figure 10) it takes as much as 22% particulates to increase  $G^*/\sin(\delta)$  by one grade, 13% when  $K_E$  is 6, and only 9% when  $K_E$  is 12. Since most of the powders studied had  $K_E$  between 2 and 6, it can be stated that between 13 and 22% particulates change the high temperature grade by 6°C. Higher the  $K_E$ , the more sensitive is the grade to the addition of fillers (stiffening effect).

At the lower end, a similar behavior can be observed. However, it is much subdued at this end for it takes 18% particulates to increase  $S$  by one grade at  $\phi_m$  of 0.35 and  $K_E$  of 6. It is not known if these parameters  $\phi_m$  and  $K_E$ , will remain the same as the temperature is lowered. If this behavior can be controlled then it is possible to tailor the fines to effect the high temperature grade while not causing a change in the low temperature properties.

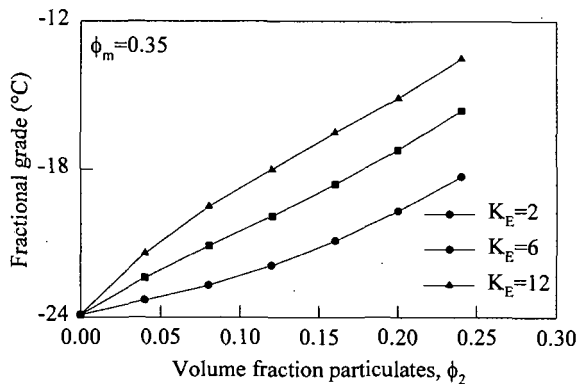


Figure 12. The effect of increasing  $K_E$  on the low-temperature grade of binders based on  $S$ .

## CONCLUSIONS

The following conclusions were made from this study:

1. Nielsen's equation was shown to fit the dependence of stiffness on volume fraction particulates,  $\phi_2$ , for thirteen fillers. The parameters in the equation estimates the maximum packing fraction  $\phi_m$  and generalized Einstein coefficient,  $K_E$ . Thus the dependence of stiffness on volume fraction can be predicted by knowing these two fundamental parameters.
2. The phase angle did not vary systematically with  $\phi_2$ . The overall change in the phase angle with the addition of up to 25 volume percent particulates was less than 2 degrees.
3. The  $\phi_m$  estimated from Nielsen's equation did not correlate with the  $\phi_m$  measured by compaction technique for the measured data. However, when such a comparison was made for data from literature very good correlation was observed. Thus, more study is required to completely understand the Nielsen's equation for asphalt mastics.
4. For the powders used in our study  $\phi_m$  had values of 0.29 to 0.52, and  $K_E$  had values 2.04 to 13.8.
5. The high temperature and low temperature continuous grade increased with addition of fillers. This increase was more sensitive as  $\phi_m$  decreased and as  $K_E$  increased. In other words, if  $\phi_m$  is reduced or  $K_E$  is increased, the continuous grade increased more rapidly with the addition of particulates.
6. The continuous grade which is synonymous with stiffening power is affected by not just  $\phi_m$  (which is equivalent to Rigden voids) but also to  $K_E$ , another independent parameter.

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